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Differential acceleration in the final beam lines of a Heavy Ion Fusion driver

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A long-standing challenge in the design of a Heavy Ion Fusion power plant is that the ion beams entering the target chamber, which number of order a hundred, all need to be routed from one or two multi-beam accelerators through a set of transport lines. The beams are divided into groups, which each have unique arrival times and may have unique kinetic energies. It is also necessary to arrange for each beam to enter the target chamber from a prescribed location on the periphery of that chamber. Furthermore, it has generally been assumed that additional constraints must be obeyed: that the path lengths of the beams in a group must be equal, and that any delay of "main-pulse" beams relative to "foot-pulse" beams must be provided by the insertion of large delay-arcs in the main beam transport lines. Here we introduce the notion of applying "differential acceleration" to individual beams or sets of beam at strategic stages of the transport lines. That is, by accelerating some beams "sooner" and others "later," it is possible to simplify the beam line configuration in a number of cases. For example, the time delay between the foot and main pulses can be generated without resorting to large arcs in the main-pulse beam lines. It is also possible to use differential acceleration to effect the simultaneous arrival on target of a set of beams (*e.*g., for the foot-pulse) without requiring that their path lengths be precisely equal. We illustrate the technique for two model configurations, one corresponding to a typical indirect-drive scenario requiring distinct foot and main energies, and the other to an ion-driven fast-ignition scenario wherein the foot and main beams share a common energy.

I. INTRODUCTION

A long-standing challenge in the design of a Heavy Ion Fusion power plant[1–4] is that the ion beams entering the target chamber, which number of order a hundred, all need to be routed from one or two multi-beam accelerators through a set of transport lines. After emerging from the accelerator(s) and undergoing conjoined transport over some distance, the beams are separated, They are divided into groups, which each have unique arrival times and may have unique kinetic energies. It is also necessary to arrange for each beam to enter the target chamber from a prescribed location on the periphery of that chamber. Furthermore, it has generally been assumed that additional constraints must be obeyed: that the path lengths of the beams in a group must be equal, and that any delay of "main-pulse" beams relative to "foot-pulse" beams must be provided by the insertion of large delay-arcs in the main beam transport lines.

Here we introduce the notion of applying "differential acceleration" to individual beams or sets of beam at strategic stages of the transport lines. That is, by accelerating some beams "sooner" and others "later," it is possible to simplify the beam line configuration in a number of cases. For example, the time delay between the foot and main pulses can be generated without resorting to large arcs in the main-pulse beam lines. In some cases, *e.*g., when two accelerators are arranged at opposite sides of the chamber, this can reduce the need for beam bending, known to be a source of emittance growth in space- charge-dominated beams.

It is also possible to introduce "trim" accelerating elements on the individual final beam lines. These can enable differential acceleration to provide for the simultaneous arrival on target of a set of beams (*e.*g., for the foot-pulse) without requiring that their path lengths be precisely equal. This can dramatically simplify the design of the three-dimensional "railroad yard" leading to the chamber, and reduce its cost. It may also be possible to reduce some components of the required geometrical precision by this means, though we have not assessed this.

The layout of this paper is as follows. Section II reviews typical final beamline layouts for indirectly-driven[5,6] and directly-driven[7] targets, and some earlier work on their overall configurations. Section III presents the differential acceleration concept and the simple calculation used to generate the examples. Section IV illustrates the technique for two model configurations. One corresponds to a typical indirect-drive scenario, requiring distinct foot and main energies,[5,6]. The other corresponds to an ion-driven fast-ignition target (the "X-target")[8,9] which requires only single-sided drive, and in which the foot and main beams share a common energy. Finally, Section V offers a few closing comments.

II. FINAL BEAM LINE LAYOUTS

In a "traditional" indirect-drive HIF power plant concept, clusters of beams approach the target chamber from two sides, each of which fans out into a set of cones. To simplify the final beam routing, the cone angles are kept as small as possible, consistent with final focusing magnet shielding requirements and other constraints. The "Robust Point Design" (RPD) is an example of such a

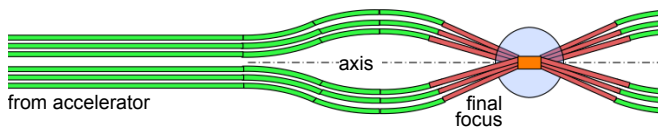system.[10] The general geometry is illustrated in Fig. 1.

FIG. 1. Conceptual layout of a final beam layout for an HIF driver intended to work with indirectly driven targets.

Other concepts involve directly-driven targets.[7] The most straightforward approaches assume that the beams come in from ports distributed uniformly around the periphery of the chamber in some regular pattern; these, however, complicate the chamber design, and seem to preclude the use of neutronically thick liquid walls of, *e.g.*, FLiBe. Alternatively, a "polar direct drive" approach keeps the beams on cones (typically with a larger cone angle than for indirect drive); the beams are aimed and otherwise specified so as to give uniform target drive (in some cases this may require sweeping the nominal focal spot positions during the target drive). A representative layout showing some of the beams in a direct-drive scenario is shown in Fig. 2.
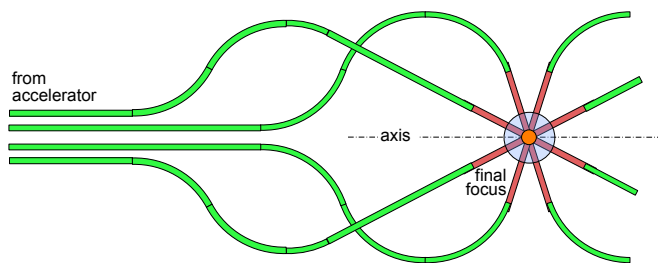

FIG. 2. Conceptual layout of a final beam layout for an HIF driver intended to work with directly driven targets.

To maintain a longitudinally quiescent beam, "ear" fields (additional components of the accelerating waveforms designed to counteract the space-charge-induced blow-off of the ends) are needed, both in the accelerator and in the transport lines.

In almost all scenarios, the beams also undergo (nonneutral) drift compression during some portion of their final transport toward their final -focusing lenses (typically, magnetic quadrupole multiplets). In this process, a head-to-tail velocity gradient or "tilt" is imparted to a beam, which then shortens and temporally compresses as it drifts. Ultimately, the inward motion in the beam frame of reference is halted by space-charge forces, leaving the beam nearly mono-energetic. This "stagnation" is beneficial because minimization of the coherent energy spread along the beam reduce the deleterious effects of chromatic aberrations on the focal spot.[13]

Pulse shaping of individual beams is sometimes assumed.[14] This is accomplished by imposing a non-uniform velocity tilt on the beam, so that it compresses in a manner which is not nearly self-similar. In contrast,

the RPD builds up the pulse shape required by stacking building-block pulses. In either case, some beam pre-configuration in advance of the final drift compression is likely to be needed, requiring additional transport length.

In power plant concepts employing a single, multi-beam linac but targets requiring two-hemisphere drive, it is necessary to use at least a pair of arcs to carry the beams from the accelerator to the vicinity of the target chamber. This is the case for both indirect-drive and direct-drive scenarios; see Fig. 3.
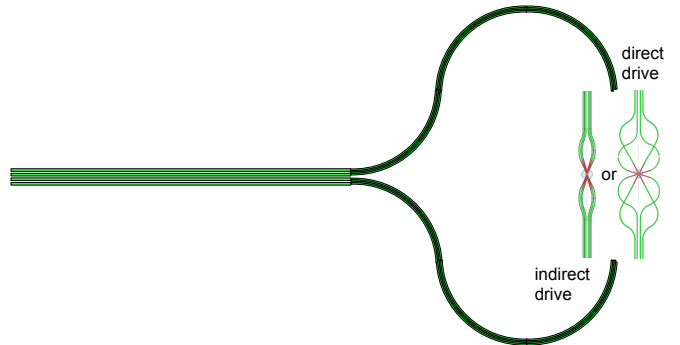

FIG. 3. Conceptual layout of arcs connecting HIF driver accelerator with final beam lines, applicable to any target requiring illumination on two hemispheres..

The late Dr. David Judd developed a conceptual design of the transport lines for an HIF power plant.[11] It is documented in a draft report, left incomplete and unpublished by Dr. Judd. More recently, a commentary on that work was developed, necessarily also as an unpublished Laboratory report; see[12]. In the scenario examined therein, the arcs are $\sim$600 m long, while the drift distance should be <240 m. Thus, the velocity "tilt" must be imposed in the arcs, or upon exit from the arcs (requiring longer transport lines). In order to produce the required time delay between foot and main pulses, Judd's work assumed separate arcs for those two groups of beams. Figure 4 shows the layout, which includes a significantly longer path length for the main-pulse beams. Note also how the beam clusters fan apart so as to enable the beams to enter at positions on their respective cones.

III. DIFFERENTIAL ACCELERATION

We now turn to the concept of differential acceleration. The linac is assumed to accelerate all beams in tandem to some intermediate kinetic energy, E_0. At that point, which we consider the starting point $z_0 = 0$ for our calculations, the main-pulse beams and the foot-pulse beams split from each other, forming two separate beam bundles. Since they are to arrive first at the target, the foot-pulse beams are immediately accelerated to their final kinetic energy, E_{foot}. This acceleration is complete when the foot beams reach the station $z = z_1$, the location of which is determined by E_0, E_{foot}, and the acceleration "gradient" (rate) G in V/m. Thenceforth, the foot
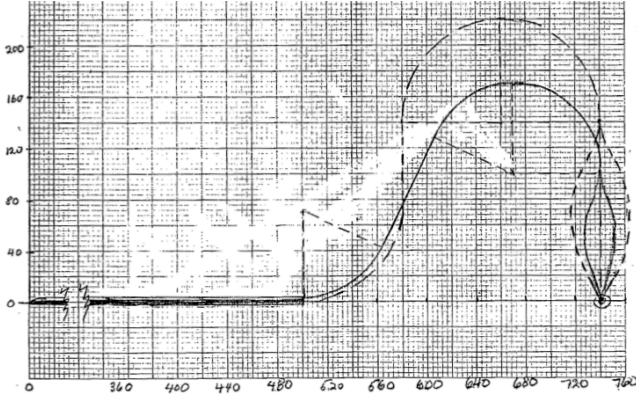
FIG. 4. Schematic of arcs connecting HIF driver accelerator with final beam lines, showing the conventional use of different path lengths to insert delay between foot and main pulses, from Ref. 11.

beams race ahead of the main beams. The acceleration of the main beams from E_0 to their final kinetic energy E_{main} begins at station z_2, and is completed by station z_3. Beyond this point, the beams begin drifting. Though the main beams are now faster then the foot beams, the latter have a large head start and the main beams never catch up. See Fig. 5, which is schematic.
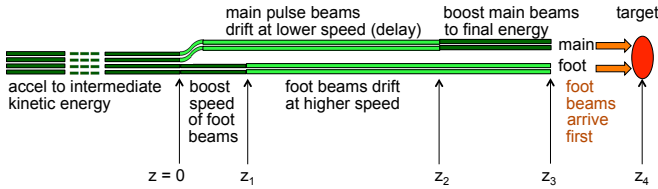

FIG. 5. Differential acceleration concept for insertion of delay between foot and main pulses; darker color denotes a region with active acceleration.

For a target requiring only single-sided (more properly, single-hemisphere) drive, this is a large simplification, since the delay arcs are entirely eliminated. However, even if the target requires that the beams come in from both hemispheres, there is a savings. In particular, it is not necessary to provide a separate beam tunnel or other shelter for two classes of beams per hemisphere (four tunnels total); rather , a single tunnel per hemisphere suffices. A possible layout is shown in Fig. 6.
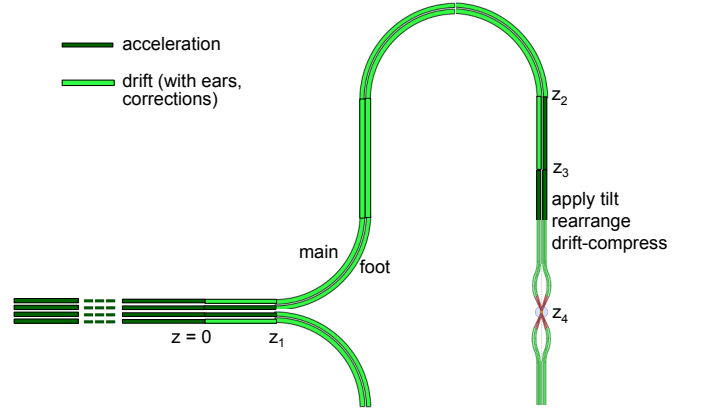

FIG. 6. Schematic of arcs connecting HIF driver accelerator with final beam lines, showing use of a common pair of arcs for both foot and main pulses.

It seems simplest to apply the final velocity tilt beginning at station z_3, in a straight section of the transport line, as shown in the figure. Though not shown in the figure, it is also assumed that small differences in path length from beam to beam, in the final "switchyard," can be accommodated via small accelerating fields applied separately to the individual beams, after the main velocity tilt has been imposed.

A simple program was written to explore representative examples of how differential acceleration can introduce the needed delay between the foot and main pulses. Assuming, for simplicity, singly-charged ions, the user-specified inputs are:

A_{ion} - ion mass, in amu
$\mathcal{E}_0$ - common ion energy at station z_0, in eV
$\mathcal{E}_{\mathrm{foot}}$ - foot beam energy, in eV
$\mathcal{E}_{\mathrm{main}}$ - main beam energy, in eV
$\mathcal{G}$ - accelerating gradient, in V/m
$\triangle z_2 = z_2 - z_1$, in m
$\triangle z_{\mathrm{drift}} = z_4 - z_3$, in m

The calculation proceeds by defining auxiliary variables corresponding to the above, in SI units. These include velocities v_0, v_{foot}, v_{main} in m/s, corresponding to the input energies, and the ion mass in kg, m. In addition, the energies in Joules are E_0, E_{foot}, E_{main}, and the accelerating gradient in J/m is g. Then:

$z_1 = (E_{\mathrm{foot}} - E_0)/g$
$z_2 = z_1 + \triangle z_2$
$z_3 = z_2(E_{\mathrm{main}} - E_0)/g$
$z_4 = z_3 + \triangle z_{\mathrm{drift}}$
$t_{1\mathrm{foot}} = m(v_{\mathrm{foot}} - v_0)/g$
$t_{1\mathrm{main}} = z_1/v_0$
$t_{2\mathrm{foot}} = t_{1\mathrm{foot}} + (z_2 - z_1)/v_{\mathrm{foot}}$
$t_{2\mathrm{main}} = z_2/v_0$
$t_{3\mathrm{foot}} = t_{2\mathrm{foot}} + (z_3 - z_2)/v_{\mathrm{foot}}$
$t_{3\mathrm{main}} = t_{2\mathrm{main}} + m(v_{\mathrm{main}} - v_0)/g$
$t_{4\mathrm{foot}} = t_{3\mathrm{foot}} + \triangle z_{\mathrm{drift}}/v_{\mathrm{foot}}$
$t_{4\mathrm{main}} = t_{3\mathrm{main}} + \triangle z_{\mathrm{drift}}/v_{\mathrm{main}}$
$\triangle t_{\mathrm{target}} = t_{4\mathrm{main}} - t_{4\mathrm{foot}}$

Here, $\triangle t_{\mathrm{target}}$ is the difference between the arrival times of the foot and main pulses at the target plane.

IV. EXAMPLES

The first example corresponds to a possible indirect-drive distributed-radiator target. The parameters for this case are shown in Table I. In cases such as this one, where the final kinetic energies of the foot and main differ, $\triangle t_{\text{target}}$ is readily adjustable by varying $\triangle z_{\text{drift}}$.

The second example corresponds to a direct-drive distributed-radiator target; the particular target considered uses higher-energy ion beams with greater range, for both the implosion and ignition phases. The parameters for this case are shown in Table II. In this case, it is easiest to adjust $\triangle t_{\text{target}}$ by varying $\triangle z_2$.

A_{ion}	208.98 amu						
$\mathcal{G}$	3.0 MV/m						
$\triangle z_2$	375.0 m						
$\triangle z_{\text{drift}}$	200.0 m						
$\mathcal{E}_0$	2.5 GeV	v_0	48.0 m/us	β_0	0.16
$\mathcal{E}_{\text{foot}}$	3.0 GeV	v_{foot}	52.6 m/us	β_{foot}	0.176
$\mathcal{E}_{\text{main}}$	4.0 GeV	v_{main}	60.8 m/us	β_{main}	0.203
z_1	166.7 m	$t_{1\text{foot}}$	3310.9 ns	$t_{1\text{main}}$	3468.9 ns
z_2	541.7 m	$t_{2\text{foot}}$	10435.8 ns	$t_{2\text{main}}$	11273.9 ns
z_3	1041.7 m	$t_{3\text{foot}}$	19935.8 ns	$t_{3\text{main}}$	20463.4 ns
z_4	1241.7 m	$t_{4\text{foot}}$	23735.8 ns	$t_{4\text{main}}$	23754.2 ns
$\triangle t_{\text{target}}$	18.5 ns						

TABLE I. Parameters for beam lines employing differential acceleration to drive a target that requires different kinetic energies for foot and main pulses.

A_{ion}	84.91 amu						
$\mathcal{G}$	3.0 MV/m						
$\triangle z_2$	100.0 m						
$\triangle z_{\text{drift}}$	300.0 m						
$\mathcal{E}_0$	12.0 GeV	v_0	165.1 m/us	β_0	0.551
$\mathcal{E}_{\text{foot}}$	13.0 GeV	v_{foot}	171.9 m/us	β_{foot}	0.573
$\mathcal{E}_{\text{main}}$	13.0 GeV	v_{main}	171.9 m/us	β_{main}	0.573
z_1	333.3 m	$t_{1\text{foot}}$	1978.1 ns	$t_{1\text{main}}$	2018.5 ns
z_2	433.3 m	$t_{2\text{foot}}$	2559.9 ns	$t_{2\text{main}}$	2624.0 ns
z_3	766.7 m	$t_{3\text{foot}}$	4499.2 ns	$t_{3\text{main}}$	4602.1 ns
z_4	1066.7 m	$t_{4\text{foot}}$	6244.6 ns	$t_{4\text{main}}$	6347.5 ns
$\triangle t_{\text{target}}$	102.9 ns						

TABLE II. Parameters for beam lines employing differential acceleration to drive a target (*e.*g., an "X-target" fast-ignition design) that requires a common kinetic energy for foot and main pulses.

V. DISCUSSION

This work has introduced the basic concept of differential acceleration. While the need for drift compression is mentioned, no calculations combining that process with differential acceleration were performed. The related notion of "mid-course corrections" during final transport and/or drift compression was considered by Judd and others.[11] Similarly, the use of "ear" fields to control the beam ends during final transport was considered. Finally, we have not worked out an example of the three-dimensional routing of beams as they approach the target chamber, using differential acceleration. Nonetheless, it seems plausible that an HIF power plant may be made more attractive through the application of one or more of the manipulations described herein.

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